APPENDIX G

RELIABILITY ANALYSIS FOR SEEPAGE AND PIPING FAILURE, WHITTIER NARROWS DAM

G-1. Introduction.

a. Whittier Narrows Dam is a 16,900-foot long embankment dam located 10 miles east of downtown Los Angeles. Condominiums and single-family residences line the downstream toe, less than 150 feet from the embankment. The dam is primarily used for flood control and groundwater recharge. Incidents of seepage sand boils and ponding on the downstream toe of the 4,000-foot long west embankment during relatively low pools led to a reevaluation of the existing seepage control system. The amount of seepage is directly related to pool elevation and the data shows the relationship between piezometric levels, seepage amount and pool elevation is constant over time.

b. The dam is founded on Recent Holocene Alluvium, which ranges in thickness from zero to about 120 feet. The upper foundation materials consist of loose to medium dense silty sand. The material becomes increasingly coarse and dense with depth. At depths greater than 30 feet, the material is typically very dense and most commonly classifies as poor to well graded sand with gravel.

c. The groundwater elevation downstream of the embankment ranges between the surface and 30 feet below surface and is very sensitive to seasonal conditions, groundwater recharge operations, and pool elevation behind the embankment. During flood control operations the groundwater rises very rapidly.

G-2. Computational Model.

a. A finite element seepage program was used to determine the flow lines and head drops in the vicinity of the toe. The escape gradient was then determined and the factor of safety against flotation was calculated. The conditional probability of failure was calculated for a pool elevation at elevation 229 feet, the approximate 100-year event. (For a total annualized risk assessment a range of pool levels would be analyzed to determine the total annualized consequences. This is a case where the analysis of pool elevations above the failure threshold is not required and only few pool elevations below the failure threshold elevation are required to determine consequences and related risks.)

b. The soils at the top of the foundation, which tend to be finer-grained and less permeable, were represented as a 10-ft thick semi-pervious top layer. The thickness of the deeper alluvium, which is coarser-grained and more permeable, varies from about 40 ft to about 120 ft along the length of the embankment. Density tests taken in the upper soils provide a range of unit weights, the average being 117.1 pcf.

c. Permeabilities for the foundation material were estimated based on data from pump tests, large-scale insitu tests and familiarity with similar materials. Due to the low permeability of the embankment relative to the foundation, flows through the embankment are insignificant. For all materials, the ratio of the horizontal to vertical permeabilities is assumed to be 4:1.

d. Sixty-two relief wells, spaced on 50-foot centers are located just downstream of the west embankment. Though approximately one-third of the wells no longer functioned, however the analysis assumed that the entire system functioned as designed.

e. In the finite element analyses, the relief wells were represented by a column of elements five feet wide and 50 ft high, at the location of the relief wells. Values of permeability were assigned to the elements in this column such that the same amount of head loss would occur through the column of elements as through a relief well. Head losses in the relief wells were based on the results of the pump tests.

G-3. Probabilistic Analyses.

a. The variation in the soil conditions along the dam made it difficult to select a single set of conditions for deterministic analyses. And while parametric analysis is useful for evaluating the relative importance of a variable, it provides no relationship between the value and its likelihood of occurrence. Probabilistic analyses (reliability analyses) are better able to cope with variable conditions because the combined effects of variations in all of the parameters can be evaluated on a logical theoretical basis.

b. A reliability analysis spreadsheet was developed which uses the Taylor series method to evaluate the coefficient of variation of the factor of safety, and computes the log normal reliability index (β_{LN}).

c. The reliability index (β_{LN}) is directly and uniquely related to "probability of unsatisfactory performance." "Probability of unsatisfactory performance" merely indicates the likelihood that some adverse event or condition, in this case a factor of safety less than 1.0, occurs. It is important to make clear that what is being computed in these reliability analyses is the probability that the factor of safety against the beginning of internal erosion and piping may be less than 1.0. This would be an undesirable condition, but it would not automatically result in failure of the dam. Depending on subsequent events, it might or might not result in serious consequences.

d. The Taylor series method involves these steps, as explained in the U. S. Army Corps of Engineers ETL 1110-2-556:

(1) For each random variable, the expected value and the standard deviation are determined. In this case there were five random variables: the permeability of the top stratum, the permeability of the lower stratum, the thickness of the lower stratum, the well flow losses in the relief wells, and the unit weight of the top stratum.

(2) The values of standard deviation were estimated using the "Three Sigma Rule" (Dai and Wang, 1992). The Three-Sigma Rule says that the lowest conceivable value is about

three standard deviations (three sigma) below the expected value, and the highest conceivable value is about three standard deviations above the expected value. The standard deviation is determined by estimating the highest and lowest conceivable values based on all available data and judgement.

(3) The values of standard deviation are computed using the following formula:

$$\sigma = \frac{HCV - LCV}{6}$$

where HCV = the highest conceivable value of the variable, and LCV = the lowest conceivable value of the variable.

(4) Seepage analyses are performed, and factors of safety against erosion at the downstream toe of the dam due to upward seepage are calculated.

(5) Expected values and standard deviations were determined and are presented in Table G-1.

Table G-1. Expected Value and Standard Deviation for the Probability Analysis

	T_{LOWER}, ft	k_{UPPER}, fpd	k_{LOWER}, fpd	k_{WELL}, fpd	γ_{SAT}, pcf
Expected Value	80	40	500	3200	117.1
Standard Deviation	40	15	150	800	9.1

G-4. <u>Results</u>.

a. The results of the reliability analysis calculations based on the finite element analyses are shown in Table G-2 below.

b. The results of this reliability study indicated that there was a 30 percent conditional probability that the factor of safety against the beginning of erosion and piping may be less than 1.0 for a pool elevation equal to the 100 year event. In addition to the analysis performed using the finite element method, a second analysis using a spreadsheet based on relief well equations in EM 1110-2-1901 indicated a 34 percent conditional probability of unsatisfactory performance for the 100-year pool elevation.

c. Table A-1 (page B-133) of Engineering Technical Letter 1110-2-556, categorizes reliability indexes and probabilities of unsatisfactory performance. By this classification, the condition at the West dam is 'Hazardous." Therefore, the condition at the west embankment represents an unacceptably high chance that erosion and piping will begin if the reservoir reaches its design pool elevation, 229 feet. As a result, the District remediated the problem by constructing a berm with a gravel drain on the downstream toe.

Table G-2. Taylor Series Reliability Calculations Based on Finite Element Analysis Results.

Analysis No.	T_{LOWER} (ft)	k_{UPPER} (fpd)	k_{LOWER} (fpd)	k_{WELL} (fpd)	γ_{SAT} (pcf)	i	FS	ΔFS	$(\Delta FS/2)^2$
1	80	40	500	3200	117.1	0.75	1.17		
2	40	40	500	3200	117.1	0.62	1.41		
3	120	40	500	3200	117.1	0.80	1.10	0.318	0.025
4	80	55	500	3200	117.1	0.70	1.25		
5	80	25	500	3200	117.1	0.80	1.10	0.157	0.006
6	80	40	650	3200	117.1	0.82	1.07		
7	80	40	350	3200	117.1	0.67	1.31	0.239	0.014
8	80	40	500	4000	117.1	0.72	1.22		
9	80	40	500	2400	117.1	0.78	1.12	0.094	0.002
10	80	40	500	3200	126.2	0.75	1.36		
11	80	40	500	3200	108.0	0.75	0.97	0.389	0.038
								sum =	0.086
								V_{FS} =	0.251
								β_{LN} =	0.509